MILLING MACHINE PRACTICE

THE CINCINNATI MILLING MACHINE COMPANY
CINCINNATI, OHIO, U. S. A.

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CINCINNATI, OHIO · U. S. A.

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By Hans Ernst and Mario Martellotti

1. ANALYSIS OF THE PROCESS OF MILLING

FUNDAMENTAL CONCEPT.—The milling process may be considered as a method of metal removal in which the portion of the work piece that is to be removed is projected into the space dominated by a rotating body carrying one or more individual cutting teeth. The profile of the finished surface produced on the work piece, therefore, is determined by the intersection of a plane, perpendicular to the motion of the work piece, and the outline of the body of revolution generated by the rotating cutter.

Two main classes of milling operations are:

1. Face Milling, in which the finished surface mainly is parallel to the face of the cutter.

2. Peripheral Milling (including slab and form milling), in which the finished surface mainly is parallel to the periphery of the cutter.

CHARACTERISTIC FORM OF MILLING CHIP.—Because of the limited period of engagement of each tooth with the work piece, the removal of metal in milling is accomplished by the separation of small individual chips. The rotary motion of the cutter and the translatory motion of the work piece combine to produce a chip whose cross-section varies from instant to instant as the direction of motion of a tooth changes with respect to direction of motion of the work piece. Chip thickness is a maximum at the instant that these motions are perpendicular to each other, and substantially zero when they are parallel.

SURFACE GENERATED IN MILLING.—In peripheral milling, two distinct methods are used:

Up-milling.—The work piece advances toward the cutter from the side where the teeth are moving upward. The cutter rotates against the direction of the feed. The chip thickness is a minimum at the beginning of the cut and a maximum at the end.

Down-milling.—The work piece advances toward the cutter from the side where the teeth are moving downward. The cutter rotates in the same direction as the feed. The chip thickness is a maximum at the beginning of the cut, and a minimum at the end.

Fig. 1 compares the shape of milling chips produced by these two methods, the difference in shape being exaggerated by the use of a large feed per tooth. In both methods the path of a tooth through the work material is a prolate trochoid. Its actual shape will vary with changes in rate of feed, diameter of cutter, depth of cut, and cutting speed. Fig. 1 shows that the actual rake and clearance angles change continually as the tooth forms a chip. In up-milling, the actual clearance angle θ is greatest at the beginning of the tooth contact with the work, decreasing to a minimum value of θ_1 when the tooth leaves the work. The actual rake angle, however, has a minimum value α at the beginning of the cut, increasing to maximum value α_1 at the point of leaving the work. In down-milling, the actual clearance angle θ is least at the beginning of the cut and greatest, θ_1, at the end; the actual rake angle α is greatest at the beginning of the cut, and least, α_1, at the end.

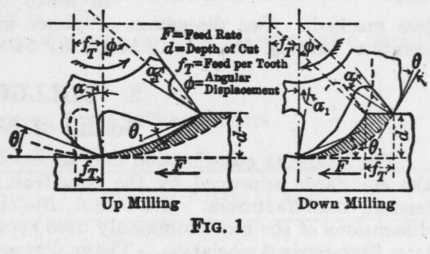


Fig. 1

In this respect, milling differs radically from other machining processes, as turning, planing, etc., in which clearance and rake angles remain constant throughout the cut.

CHIP FORMATION.—Up-milling and down-milling produce surfaces of entirely different character, the reason lying in the nature of the process of chip formation. When a cutting tool engages a work piece, the material immediately ahead of the cutting edge is at first compressed and escapes by flowing in a direction parallel to the face of the tool. See Fig. 2. As the tool continues to advance, however, escape in this direction becomes

increasingly difficult; the pressure on the tool rises; the stress in the material further ahead of the tool increases, finally reaching a value great enough to cause rupture or flow in a plane roughly perpendicular to the face of the tool. If the material is relatively brittle, or the thickness of chip is great, a definite rupture will occur in this plane. The entire portion of severed material then will move out of the path of the advancing tool, and permit the engagement of a fresh portion. The chip will not be a continuous ribbon, but a series of individual segments more or less closely joined. This type of chip is known as a segmental chip.

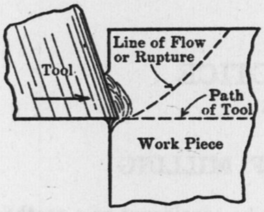


Fig. 2

If the material is relatively ductile, definite successive ruptures will not take place; instead, the material ahead of the tool will yield by plastic flow over a broad region. As this material (*A*, Fig. 3) is forced out of the path of the advancing tool, it separates from the initially compressed portion *B*, which is held by frictional contact with the tool face. The body of the chip passes off as a substantially solid ribbon, with flow lines perpendicular to the tool face. The wedge-shaped portion *B*, with flow lines parallel to the tool face, remains to form the so-called *built-up edge*. This type of chip generally is known as a flow-type chip. The built-up edge is added to continuously by material compressed at point *C*, but is periodically reduced by fragments, as *D* and *E*, torn off both the chip and work piece, respectively.

Roughness of a machined surface is due solely to the presence of fragments such as *E*; consequently, for good finish, their magnitude should be kept to a minimum by so arranging conditions that the stable size of the built-up edge itself is a minimum. Such arrangements include: 1. Decrease in chip thickness; 2. Increase in rake angle; 3. Increase in tool sharpness; 4. Increase of cutting speed; 5. Use of cutting fluid; 6. Use of work material of lower ductility. See H. Ernst and M. Martellotti, Metal Cutting, *Mech. Engg.*, Aug., 1935.

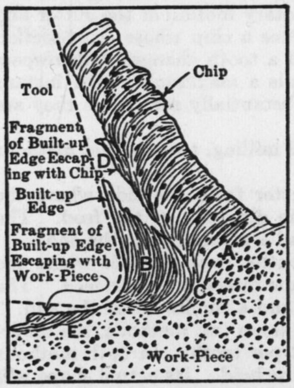


Fig. 3

In up-milling, the portion of the finished surface which is produced by a tooth is formed at the beginning of its contact with the work piece, when the chip thickness is extremely small. Hence, the built-up edge itself is very small, and the resultant surface is smooth and shiny. In down-milling an element of the finished surface is produced at the end of the tooth engagement with the work. With a ductile material such as a low-carbon steel, where the built-up edge is large, the latter persists to the extreme end of the chip; thus the escape of fragments likewise persists, and produces a somewhat torn finish similar to that obtained by planing or shaping. With a less ductile material, such as a high carbon steel, the built-up edge is smaller; hence, the difference in finish between up-and-down methods of milling is less marked. (See discussion of paper by O. W. Boston and C. E. Kraus, The Elements of Milling, *Trans.* A.S.M.E., RP 54–4, 1932, p. 96.)

2. MILLING CUTTERS

Forms of Milling Cutters

The following classification and nomenclature relative to milling cutters are based on the standards approved by the American Standards Association, and adopted by the leading manufacturers. See A.S.A. *Bulletin*, 5C–1930. Tables 1 to 9 show principal dimensions of the most commonly used types of milling cutters, as approved by the American Standards Association. These dimensions have been adopted as standard by the cutter manufacturers.

CLASSIFICATION BASED ON RELIEF OF TEETH.—1. Profile Cutters.—All forms of cutters which are sharpened by grinding on the periphery of the teeth, the clearance (or relief) being obtained by grinding a narrow land back of the cutting edge. Where the cutting edges are of curved or irregular shape, they are designated as Shaped Profile Cutters.

2. Formed Cutters.—All cutters where the eccentric relief back of the cutting edge is of the same contour as the cutting edge itself. These cutters are sharpened by grinding the face of the teeth.

CLASSIFICATION BASED ON METHOD OF MOUNTING.—1. Arbor Cutters.— A cutter with hole for mounting on arbor.

2. Shank Cutters have either a straight or taper shank integral with the cutter.

3. Facing Cutters are designed to be attached directly to spindle end or to stub arbor.

GENERAL TYPES OF CUTTERS.—The commonly used types of cutters, and the work to which they are adapted are:

The Plain Milling Cutter is a cylinder with teeth on the circumferential surface only. It is used to produce a flat surface parallel to the axis of the cutter. Plain milling cutters are made in a wide variety of diameters and widths, for the various requirements of slab milling. They generally have helical teeth. The helical form enables each tooth to take a cut gradually, thus reducing shock and minimizing tendency to chatter. Cutters with a helix angle of 25 to 45 deg. commonly, but incorrectly, are termed *spiral mills*; if helix angle is more than 45 deg. the cutter generally is known as a *helical mill.*

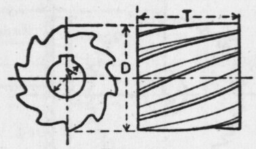


FIG. 4

The helical mill, which may be either of the shank or hole type, is free cutting and particularly desirable for light cuts on soft steel or brass. It can run at high speeds and, therefore, produces a good finish. It can be used to advantage for profiling work such as cam milling, and for milling intermittent surfaces. The shank type, with pilot end, commonly is used for elongating slots. For general slab milling, the helical mill is not as efficient as the common "spiral" mill.

Table 1.—Dimensions of Heavy Duty Plain Milling Cutters

See Fig. 4

Cutter Diam., *D*, in.			Diam. of Hole, *A*, in.		Nominal Widths of Face, *T*, in.
Nominal	Max.	Min.	Max.	Min.	
2 1/2	2.515	2.485	1.001	1.000	2, 2 1/2, 3, 4
3	3.015	2.985	1.251	1.250	2, 2 1/2, 3, 4, 6
4	4.015	3.985	1.501	1.500	2, ... 3, 4, 6
4 1/2	4.515	4.485	2.001	2.000	.. .. 6, 12

LIMITS OF *T*

Nominal	2.0	2 1/2	3.0	4.0	6.0	12.0
Maximum	2.010	2.520	3.020	4.020	6.020	12.020
Minimum	2.000	2.500	3.000	4.000	6.000	12.000

The Side Milling Cutter is a plain milling cutter of cylindrical form with teeth on the circumferential surface and on both sides. The side teeth extend a portion of the distance from the circumference to the axis. Half side and interlocking side milling cutters also are made. Side milling cutters are used in a large variety of work. Two or more of them often are placed on the same arbor with a space between them, they then being known as straddle mills.

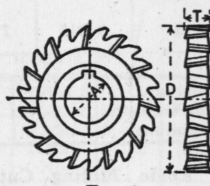


FIG. 5

Straddle Mills are used to advantage where the work is to be milled on two parallel sides; *e.g.*, bolt heads, tongues, etc.

Table 2.—Dimensions of Stagger Tooth Milling Cutters

See Fig. 5

Cutter Diam., *D*, in.			Diam. of Hole, *A*, in.		Nominal Widths of Face, *T*, in.
Nominal	Max.	Min.	Max.	Min.	
2 1/2	2.515	2.485	0.876	0.875	.... 1/4, 5/16, 3/8, ... 1/2 ... ...
3	3.015	2.985	1.001	1.000	3/16, 1/4, 5/16, 3/8, ... 1/2, 5/8, 3/4 ... ..
4	4.015	3.985	1.251	1.250	.... 1/4, 5/16, 3/8, 7/16, 1/2, 5/8, 3/4, 7/8 ..
5	5.015	4.985	1.251	1.250	.... 1/2, 5/8, 3/4 ... ..
6	6.015	5.985	1.251	1.250	.... 3/8, ... 1/2, 5/8, 3/4, 7/8, 1
8	8.015	7.985	1.501	1.500	.... 3/8, ... 1/2, 5/8, 3/4, ... 1

LIMITS OF *T*

Nominal	3/16	1/4	5/16	3/8	7/16	1/2	5/8	3/4	7/8	1
Maximum	0.1875	.2500	.3125	.3750	.4375	.5000	.6250	.7500	.8750	1.0000
Minimum	0.1870	.2495	.3120	.3745	.4370	.4995	.6245	.7495	.8740	.9990

Interlocking Cutters are used to mill slots to a standard width. They are maintained at a constant width by thin shims or collars between the inner hubs.

Staggered Tooth Milling Cutters are cylindrical cutters with the cutting teeth on the circumferential surface only. Alternate teeth are of opposite helix angle. See Fig. 5. The side teeth extending from the circumference a short distance towards the axis are for chip clearance only. They are not ground for cutting purposes. This type of cutter is used to obtain exact width of slots and is the most efficient type for milling slots where depth exceeds width. Because of the alternate right- and left-hand helix angle of the teeth, with considerable undercut, these cutters can remove large amounts of metal without vibration or chatter. The free cutting action makes possible an increased feed and speed, without detriment to the production of smooth, accurate work.

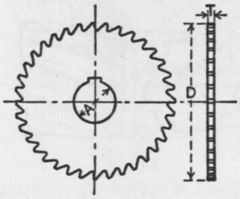


FIG. 6

Metal Slitting Saws are plain milling cutters with sides relieved or "dished" to give side clearance. They generally are made $^3/_{16}$ in. thick or less, and usually have more teeth for a given diameter than a plain milling cutter. They are used to cut off work, or to mill very narrow slots. Slitting saws also are made with side teeth similar to side milling cutters, and with staggered teeth, similar to staggered tooth milling cutters. The metal slitting saw with staggered teeth usually is made $^3/_8$ to $^3/_{16}$ in. thick, and is used for heavy sawing in steel.

Table 3.—Dimensions of Metal Slitting Saws

See Fig. 6

Cutter Diam., *D*, in.			Diam. of Hole, *A*, in.		Nominal Thicknesses, *T*, in.						
Nominal	Max.	Min.	Max.	Min.							
2 1/2	2.515	2.485	0.876	0.875	1/32,	3/64,	1/16,	3/32,	1/8	....	...
3	3.015	2.985	1.001	1.000	1/32,	3/64,	1/16,	3/32,	1/8,	5/32	...
4	4.015	3.985	1.001	1.000	1/32,	3/64,	1/16,	3/32,	1/8,	5/32,	3/16
5	5.015	4.985	1.001	1.000	....	....	1/16,	3/32,	1/8,	5/32,	3/16
			1.251	1.250	....	....	....	....	1/8	....	...
6	6.015	5.985	1.001	1.000	....	....	1/16,	3/32,	1/8,	....	3/16
			1.251	1.250	....	....	....	....	1/8,	....	3/16
7	7.015	6.985	1.001	1.000	....	....	1/16,	....	1/8	....	...
			1.251	1.250	....	....	....	....	1/8,	....	3/16
8	8.015	7.985	1.001	1.000	....	....	....	....	1/8	....	...
			1.251	1.250	....	....	....	....	1/8,	....	3/16

LIMITS OF *T*

Nominal	1/32	3/64	1/16	3/32	1/8	5/32	3/16
Maximum	0.0322	.0478	.0635	.0947	.1260	.1572	.1885
Minimum	0.0302	.0458	.0615	.0927	.1240	.1552	.1865

Angle Milling Cutters are made both **single angle** and **double angle**, with teeth on the conical surfaces. See Figs. 7 and 8. Single angle cutters are made both with and without teeth on one or both of the flat sides. Angle cutters are used for various fluting operations, or for milling the edge of a piece to a given angle.

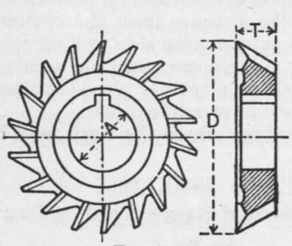


FIG. 7

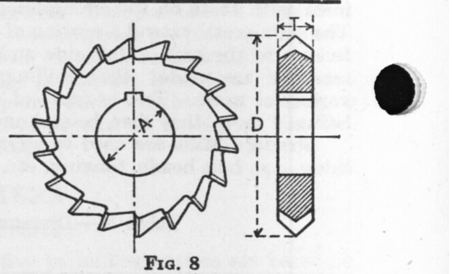


FIG. 8

Table 4.—Dimensions of Angle Milling Cutters

Cutter Diam., *D*, in.			Diam. of Hole, *A*, in.		Single Angle Cutter, Fig. 7* Thickness, *T*, in.			Double Angle Cutter, Fig. 8† Thickness, *T*, in.		
Nominal	Max.	Min.	Max.	Min.	Nominal	Max.	Min.	Nominal	Max.	Min.
2 1/2	2.515	2.485	0.876	0.875	1/2	0.515	0.485	....	....	....
2 3/4	2.765	2.735	1.001	1.000	1/2	.515	.485	1/2	0.515	0.485
3	3.015	2.985	1.251	1.250	1/2	.515	.485	....	....	....

* Included angle 45 or 60 deg. ±10 min. † Included angle, 45, 60 or 90 deg. ±10 min.

End Mills are cutters with teeth on the circumferential surface and on one end. See Fig. 9. The teeth may be either parallel to the axis of rotation or helical, and either right or left hand. End mills of moderate angle commonly are called spiral end mills. End mills are made of five general types, *viz.*, Solid end mill; two-lip end mill or slotting mill; shell end mill; hollow mill; helical end mill.

Solid End Mills are used for light milling operations, as the milling of slots, profiling, and facing narrow surfaces. The teeth are integral with the shank, which may be either straight or tapered.

Two-lip End Mills comprise a shank cutter with two cutting teeth on the circumferential surface, and end teeth cut to the center. Flutes are either straight or helical. The cutter can be sunk into the material and then fed longitudinally. A depth of cut equal to one-half the diameter of the mill usually can be taken from the solid stock.

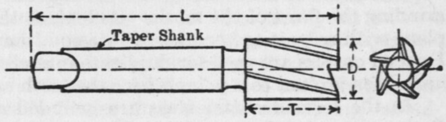


FIG. 9

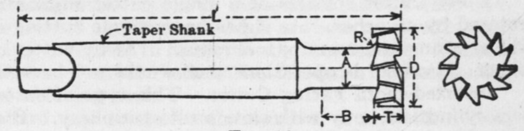


FIG. 10

Shell End Mill.—Teeth are cut on the circumferential surface and on one end. See Fig. 11. The tooth end is recessed to receive a nut or screw head for holding the cutter on the stub arbor. It usually is driven from the key slot across the back face. The teeth may be parallel to the axis of rotation, or helical, and either right or left hand. This type of milling cutter should be used in preference to the solid end mill whenever possible, because it is cheaper to replace when worn out or broken.

Hollow Mill.—A cutter of tubular construction with teeth on one end, and having an internal clearance. The internal clearance sometimes is obtained by a plain tapered hole with back taper and sometimes by internal cleared flutes. The hollow mill generally is used for producing bosses or cylindrical projections from solid bodies.

T-slot Cutter.—A shank cutter designed for milling T-slots. See Fig. 10. The teeth are on the circumferential surface and both sides. In making a T-slot, a groove first is cut with an ordinary side milling cutter or a two-lipped end mill. The wide groove at the bottom then is cut with the T-slot cutter.

Table 5.—Dimensions of Taper Shank End Mills. (See Fig. 9)

Diam. of Cutter, *D*, in.			Brown & Sharpe Taper Shank No.	Length of Cut, *T*, in.	Overall Length, *L*, in.	Diam. of Cutter, *D*, in.			Brown & Sharpe Taper Shank No.	Length of Cut, *T*, in.	Overall Length, *L*, in.
Nominal	Max.	Min.				Nominal	Max.	Min.			
1/4	0.2650	0.2500	5	5/8	2 13/16	3/4	0.7650	0.7500	7	1 1/4	5 1/4
5/16	.3275	.3125	5	11/16	2 7/8	7/8	0.8900	0.8750	7	1 7/16	5 7/16
3/8	.3900	.3750	5	3/4	2 15/16	1	1.0150	1.0000	7	1 5/8	5 5/8
7/16	.4325	.4375	5	7/8	3 1/16	1 1/8	1.1400	1.1250	9	1 3/4	7
1/2	.5150	.5000	5	15/16	3 1/8	1 1/4	1.2650	1.2500	9	2	7 1/4
1/2	.5150	.5000	7	15/16	4 15/16	1 1/2	1.5150	1.5000	9	2 1/4	7 1/2
9/16	.5775	.5625	7	1	5	1 3/4	1.7650	1.7500	9	2 1/2	7 3/4
5/8	.6400	.6250	7	1 1/8	5 1/8	2	2.0150	2.0000	9	2 3/4	8

Table 6.—Dimensions of Taper Shank T-slot Cutters. (See Fig. 10)

Nominal Bolt Size, in.	Cutter Diam., *D*, in.		Thickness of Cutter, *T*, in.		Diam. of Neck,* *A*, in.		Length of Neck, *B*, in.	Fillet Radius, *R*, in.	Brown & Sharpe Taper Shank No.	Overall Length, *L*, in.
	Max.	Min.	Max.	Min.	Max.	Min.	Min.	Max.		
1/4	0.562	0.552	0.234	0.229	0.265	0.260	3/8	0.007	5	2 5/8
5/16	.656	.646	.265	.260	.328	.323	7/16	.007	5	2 23/32
3/8	.781	.771	.328	.323	.406	.401	9/16	1/64	7	4 13/16
1/2	.968	.958	.390	.385	.531	.526	11/16	1/64	7	5
5/8	1.249	1.239	.484	.479	.656	.651	7/8	1/64	7	5 1/4
3/4	1.468	1.458	.625	.620	.781	.776	1 1/16	1/64	9	6 7/8
1	1.843	1.833	.828	.823	1.031	1.026	1 1/4	1/64	9	7 1/4
1 1/4	2.218	2.208	1.093	1.088	1.281	1.276	1 9/16	1/64	9	7 13/16
1 1/2	2.655	2.645	1.343	1.338	1.531	1.526	1 15/16	1/64	10	10 3/8

* Neck diameters as given are to be used with American Standard T-slots.

The Woodruff Key Seat Cutter is made in the **shank** and **arbor** type. The shank type generally has teeth on the circumferential surface only, with the sides slightly relieved for clearance. The arbor type generally is used in sizes larger than 2 in. diameter. These cutters also are made with staggered teeth. They are made with teeth on both sides which are ground for clearance only and not for cutting. Both types of cutters are used for the specific purpose of milling semi-cylindrical keyways in shafts, to permit the use of Woodruff keys.

Formed Cutters usually are of curved irregular outline. They are sharpened by grinding the faces of the teeth. So long as the face of a tooth is maintained in its original plane with respect to the axis of rotation, the contour of the tooth will remain unchanged. Formed cutters are used for duplicate interchangeable work over and over again until they have been ground to a point where the teeth are too slender to stand the strain of the work.

In the formed cutter class are included such cutters as: *Gear Cutters, Multiple Gear Cutters, Sprocket Cutters, Convex Cutters, Concave Cutters, Corner Rounding Cutters, Spline Cutters, Thread Milling* and *Hobbing Cutters*, etc.

A Fly Cutter consists of a single cutter similar in shape to a planer tool, held and rotated by an arbor. As it has but a single cutting edge, it is used but rarely outside of the experimental room or tool room. The fly cutter can be formed exactly to any desired shape. Its field is operations that would not bear the expense of a special form cutter.

Inserted-tooth Facing Cutter.—This type of cutter, generally known as a **Face Mill**, is a cylindrical body with slots on its periphery. Blades of various cutting materials, as high-speed steel, Stellite, or blades tipped with cemented carbide, are inserted in the slots. The teeth of the facing cutter are ground to cut both on the circumferential surface and on the side, as in the **Side Mill**. These cutters are adapted to be attached directly to the end of the spindle, or to a stub arbor.

Face Mills are used to face large surfaces, and are very efficient in the removal of metal.

The Heavy Duty Face Mill is made with a stronger body, and thicker and fewer blades than the light duty type. It generally is used for roughing cuts.

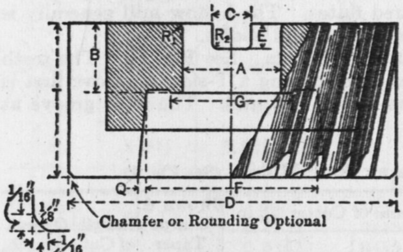


FIG. 11

The Light Duty Face Mill has a lighter body and a larger number of teeth than the heavy duty type, and is used mostly for finishing cuts. Face mills with high-speed steel inserted blades, tipped with cemented carbide, or with stellite blades, are used almost exclusively for milling cast iron and non-ferrous materials. They have more teeth and usually are run from two to three times faster than face mills with high-speed steel blades.

The inserted tooth milling cutter is most economical and useful when cutters of large dimensions are required, although they are obtainable also in diameters as low as 3 in. Almost all types of milling cutters may be made with inserted teeth. Their use is becom-

Table 7.—Dimensions of Shell End Mills. (See Fig. 11)

Size or Diam., D, in.	Width, T, in.	Hole: Diam., A, in.		Hole: Depth, B, in.		Driving Slot: Width, C, in.		Driving Slot: Depth, E, in.		Fillet Radius, R, in.	Counterbore: Diam., F, in.	Counterbore: Diam., G, in.	Counterbore: Angular Increase, Q, deg.
		Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.				
1 1/4	1	0.5005	0.5000	41/64	5/8	0.262	0.258	11/64	5/32	1/64	11/16	5/8	0
1 1/2	1 1/8	.5005	.5000	41/64	5/8	.262	.258	11/64	5/32	1/64	11/16	5/8	0
1 3/4	1 1/4	.7505	.7500	49/64	3/4	.324	.320	13/64	3/16	1/32	15/16	7/8	0
2	1 3/8	.7505	.7500	49/64	3/4	.324	.320	13/64	3/16	1/32	15/16	7/8	0
2 1/4	1 1/2	1.0005	1.0000	49/64	3/4	.387	.383	15/64	7/32	1/32	1 1/4	1 3/16	0
2 1/2	1 5/8	1.0005	1.0000	49/64	3/4	.387	.383	15/64	7/32	1/32	1 3/8	1 3/16	0
2 3/4	1 5/8	1.0005	1.0000	49/64	3/4	.387	.383	15/64	7/32	1/32	1 1/2	1 3/16	5
3	1 3/4	1.2505	1.2500	49/64	3/4	.512	.508	19/64	9/32	1/32	1 21/32	1 1/2	5
3 1/2	1 7/8	1.2505	1.2500	49/64	3/4	.512	.508	19/64	9/32	1/32	1 11/16	1 1/2	5
4	2 1/4	1.5005	1.5000	1 1/64	1	.637	.633	25/64	3/8	1/16	2 1/32	1 7/8	5
4 1/2	2 1/4	1.5005	1.5000	1 1/64	1	.637	.633	25/64	3/8	1/16	2 1/16	1 7/8	10
5	2 1/4	1.5005	1.5000	1 1/64	1	.637	.633	25/64	3/8	1/16	2 9/16	1 7/8	10
5 1/2	2 1/4	2.0005	2.0000	1 1/64	1	.762	.758	29/64	7/16	1/16	2 13/16	2 1/2	10
6	2 1/4	2.0005	2.0000	1 1/64	1	.762	.758	29/64	7/16	1/16	2 13/16	2 1/2	15

ing more and more common, even in small diameter cutters, particularly with cemented carbides.

DIRECTION OF ROTATION.—A cutter is **right-hand** if it rotates counter-clockwise, and **left-hand** if it rotates clockwise, when viewed from the front end as mounted on the spindle.

MATERIAL FOR MILLING CUTTERS.—Four classes of materials commonly used for milling cutters are: Carbon steel; high-speed steel; Stellite; cemented carbide.

High-speed Steel Cutters predominate, although carbon steel is used to some extent for screw slotting and slitting cutters and other light duty work. Practically all heavy-duty plain milling cutters are made of high-speed steel. For most classes of work, high-speed steel cutters can be run from 2 to 2 1/2 times as fast as carbon steel cutters.

Stellite is employed generally in the form of inserted blades in face mills for use on cast iron. The life of Stellite cutters is generally longer than that of similar high-speed steel cutters and the permissible cutting speed higher.

Cemented Carbide.—Inserted-blade face milling cutters, tipped with various types of cemented carbides, are (1937) replacing other types of cutters for use on cast iron. Cutting speeds normally employed are from 2 to 3 times as high as those used with high-speed steel cutters, and a considerable improvement in finish usually is obtained. Because of the extreme hardness of these carbides, a smaller allowance for finish is permissible, thus further increasing production and reducing costs.

NUMBER OF TEETH.—No standard rule exists for the number of teeth in milling cutters. Modern cutters (1937) generally are of the " coarse tooth " type, the spacing offered commercially by cutter manufacturers having been found satisfactory for most purposes.

The coarse tooth cutter provides a great chip space between successive teeth, which permits a free flow of the chip and prevents clogging of the teeth. The efficiency of the modern coarse tooth cutter is considerably higher than that of the old style fine tooth cutter. See A. L. DeLeeuw, Milling Cutters and their Efficiency, *Trans.* A.S.M.E., xxxiii, p. 245, 1911, also J. A. Hall and B. P. Graves, Effect of Variation in Design of Milling Cutters on Power Requirements and Capacity, *Trans.* A.S.M.E., lxv, p. 165, 1923.

Table 8.—Dimensions of Concave Milling Cutters. (See Fig. 12)

Diameter of Circle, C, in.			Diam. of Cutter, D, in.	Thickness of Cutter, $T\pm$ 0.010, in.	Diameter of Hole, A, in.		
Nominal	Max.	Min.			Nominal	Max.	Min.
1/8	0.1280	0.1240	2	1/4	7/8	0.876	0.875
3/16	.1905	.1865	2	3/8	7/8	.876	.875
1/4	.2530	.2490	2	7/16	7/8	.876	.875
5/16	.3155	.3115	2 1/4	9/16	7/8	.876	.875
3/8	.3780	.3740	2 1/4	5/8	7/8	.876	.875
7/16	.4405	.4365	2 1/4	3/4	7/8	.876	.875
1/2	.5040	.4980	2 1/4	13/16	7/8	.876	.875
5/8	.6290	.6230	2 3/4	1	1	1.001	1.000
3/4	.7540	.7480	3	1 3/16	1	1.001	1.000
7/8	.8790	.8730	3 1/4	1 3/8	1	1.001	1.000
1	1.0050	.9980	3 1/4	1 9/16	1	1.001	1.000

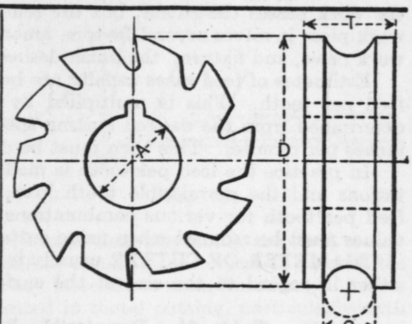


Fig. 12

Table 9.—Dimensions of Convex Milling Cutters. (See Fig. 13)

Diameter of Circle, C, in.			Diam. of Cutter, D, in.	Nominal Thickness, T, in.	Diameter of Hole, A, in.		
Nominal	Max.	Min.			Nominal	Max.	Min.
1/8	0.1270	0.1230	2	1/8	7/8	0.876	0.875
3/16	.1895	.1855	2	3/16	7/8	.876	.875
1/4	.2520	.2480	2	1/4	7/8	.876	.875
5/16	.3145	.3105	2 1/4	5/16	7/8	.876	.875
3/8	.3770	.3740	2 1/4	3/8	7/8	.876	.875
7/16	.4395	.4355	2 1/4	7/16	7/8	.876	.875
1/2	.5030	.4970	2 1/4	1/2	7/8	.876	.875
5/8	.6280	.6220	2 3/4	5/8	1	1.001	1.000
3/4	.7530	.7470	3	3/4	1	1.001	1.000
7/8	.8780	.8720	3 1/4	7/8	1	1.001	1.000
1	1.0040	.9960	3 1/4	1	1	1.001	1.000

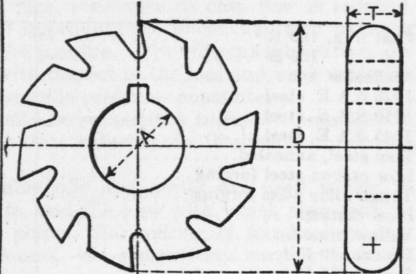


Fig. 13

Table 10.—Cutting Speed of Milling Cutters on Various Materials

Material	High-speed Steel	Stellite	Cemented Carbide
	Feet per Minute		
Cast iron, 160 B*	70–80	130–180	200–350
" " 200 B*	60–70	100–140	100–250
Malleable iron	75–95	95–110	....
1020 S.A.E. steel	75–95	....	....
1050 S.A.E. steel	70–80	....	....
3145 S.A.E. steel	60–70	....	....
Tool steel, annealed	50–55	....	....
Low-carbon steel forging	75–95	....	....
Tough alloy steel forging	60–75	....	....
Steel castings	65–75	....	....
Yellow brass	200–500	500–700	500–1000
Bronze, 40 R†	200–350	350–500	500–1000
Bronze, 75 R†	75–95	150–250	....
Aluminum	800–2500	1000–4000	1000–4000

* B = Approximate Brinell hardness number. †R = Rockwell B scale.

3. USE OF MILLING CUTTERS

CUTTING SPEED.—Because of the countless variations in conditions encountered in milling practice, fixed rules for cutting speeds are impossible. The most effective speeds are governed by the structure and hardness of the part to be machined, the amount of metal to be removed, the type of cutting material, etc. In general, cutting speed is selected to give the best compromise between maximum production and maximum life of the cutter. The values given in Table 10 are conservative and represent average practice on production jobs.

The cutting speed for finishing milling often is 40% to 80% higher than the roughing speed.

FEED RATE.—The rate of production in milling depends directly on the rate at which the work passes the cutter, but the selection of the proper feed rate for milling a given work piece involves several factors, among them being the limitations of machine, cutter, work piece, and fixture; the finish desired, etc.

Estimates of feed rates usually are based on the assumption of a certain value for the feed per tooth. This is multiplied by the number of tooth passages per minute, as determined from the desired cutting speed and tooth spacing, to obtain the feed rate in inches per minute. This then must be checked with the above limitations.

In practice the feed per tooth is made as large as possible, consistent with these limitations and the permissible tooth load. Table 11 gives average values of permissible feed per tooth for various combinations of cutting material and work material. These values must be reduced when using cutters, or work, of a relatively fragile nature.

DIAMETER OF CUTTER usually is determined by the limitations of the work piece, either in regard to the size of the surface to be milled, or interference with adjacent

Table 11.—Permissible Feed per Tooth of Milling Cutters

Material being cut	Feed per tooth, in.		
	High-speed Steel Cutter	Face Mill with Stellite Blades	Face Mill Tipped with Tungsten Carbide
Cast iron, 160 B *	0.018	0.014	0.012
" " 200 B *	.015	.012	.010
Malleable iron	.012	.008	....
1020 S.A.E. steel	.016	....	....
1050 S.A.E. steel	.014	....	....
3145 S.A.E. steel	.008	....	....
Tool steel, annealed	.010	....	....
Low carbon steel forging	.016	....	....
Tough alloy steel forging	.010	....	....
Steel castings	.015	....	....
Yellow brass	.020	.018	.012
Bronze, 40 R †	.018	.016	.012
Bronze, 75 R †	.016	.014	.010
Aluminum	.020	.020	.018

* B = Approximate Brinell Hardness Number. † R = Rockwell B Scale.

portions of work or fixture. In the case of cutters of small diameters, the limitation frequently is the size of the arbor required to support it properly.

CLEARANCE ANGLE (Relief).—The sole function of clearance or relief of the flank surface, is to prevent undue interference between it and the surface of the work. Where the direction of the motion of the flank surface, relative to the work, is parallel to the finished surface (as in the case of a shaper tool or planer tool) the clearance angle need be only sufficient to allow for the slight expansion of fragments of the built-up edge which escape with the work piece as the latter passes under the tool. Any clearance greater than the minimum amount required increases the likelihood of chatter, and reduces the life of the tool.

In the case of a peripheral cutting edge of a milling cutter, the direction of motion of the tooth relative to the direction of the feed varies with the position of the tooth in its arc of contact with the work piece. In up-milling, the motion of the tooth is parallel to the feed at the instant of engagement, and inclined thereto when leaving the work. Throughout its contact with the work piece, there is an increasing component of the feed tending to cause interference with the flank surface, and thus an additional clearance must be provided.

The additional clearance angle necessitated by the feed component depends on the diameter of the cutter, D, the feed per revolution, F_r, and the depth of cut d. Its value may be computed from

$$\theta = \frac{180}{\pi}\left\{\frac{2\,F_r}{D}\sqrt{\frac{\pi d(D-d)}{\pi(\pi D + F_r)^2 - F_r d}}\right\} \quad . \quad . \quad . \quad . \quad . \quad [1]$$

where θ is given in degrees, and D, F_r and d are in inches.

The minimum permissible clearance angle also is affected by the width of the flank (or *land*) back of the cutting edge. This should be kept to a small value, usually not greater than $^1/_{32}$ in., in order that the true clearance at the cutting edge may be as small as possible. As shown in Fig. 14, a secondary clearance angle beyond this land usually is provided to avoid interference, and to reduce the amount of material which must be removed when regrinding the cutter. The values of clearance angles commonly used range from 3 to 5 deg. for steel, to about 10 deg. for aluminum.

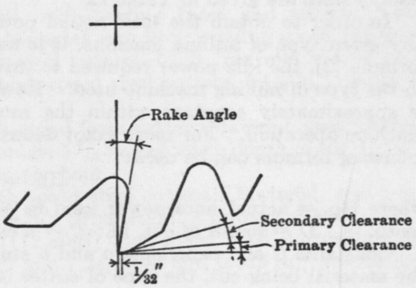


FIG. 14

RAKE ANGLE of a milling cutter (see Fig. 14) is defined as the angle by which the face of the tooth is displaced back of the radial line drawn from the center of rotation to the cutting edge. Efficiency of metal removal increases with increase in the rake angle. Consequently, the latter should be as large as possible consistent with strength. In practice, rake angles ranging from 10 to 15 deg. commonly are used.

CUTTING FLUIDS, consisting generally of oils or emulsions, are used to protect the cutter, and improve the quality of the finish. They have three main functions:

1. Cooling.—A large amount of heat is generated in metal cutting, particularly with strong ductile materials such as steel, where a flow type chip is produced. Heating of the tool point causes a reduction in resistance to abrasion, thus hastening dullness or wear. Heating of the material also may impair the finish by increasing the size of the built-up edge. For efficient cooling, a cutting fluid should have a high specific heat coefficient.

2. Lubrication.—By lubrication of the tool face, resistance to chip flow is reduced, thus reducing the size of the built-up edge and improving the finish, and also reducing the total force on the tool. This will increase the tool life. For efficient lubrication, the cutting fluid should have a low surface tension with respect to the tool and work material, and a high film strength to withstand the high specific pressures encountered.

3. Flushing of Chips.—The cutting fluid should be supplied in sufficient quantities to flush the chips away from the cutter and work, thus reducing the likelihood of marring the finished surface.

Composition.—Emulsions consisting of soluble oils and water are used widely in milling, because of their effectiveness as coolants, and the ease with which they may be used in large quantities for flushing away the chips. For milling of tough alloy steel forgings, however, heavy cutting oils often are used, the composition varying with the nature of the work and the finish required. Special compounded oils, such as sulphurized oils or chlorinated oils, are being used to an increasing extent because of their value as extreme pressure lubricants.

COMPARISON OF UP-MILLING AND DOWN-MILLING.—At various times during the past 50 years down-milling (or milling with the feed) has been advocated for particular classes of work, in view of certain advantages inherent in this method. In recent years this method has been used with special types of feed systems, designed to prevent an overrunning of the milling machine table due to the action of the cutter on the work.

When using thin metal slitting cutters the likelihood of producing crooked slots is less when cutting down than when cutting up. In milling the flutes in twist drills, and other similar operations, a longer tool life and more desirable finish has been obtained when milling down, and the holding of the work piece during the milling operation is greatly simplified. On the other hand, when milling a low carbon steel or other ductile material, the finish is much inferior than with the conventional up-milling method. The greatest practical objection to the down-milling method for heavy milling work is the danger of a serious accident if the work piece or fixture should be insecurely fastened to the table.

From the standpoint of power required there is little to choose between the two methods of milling. Careful tests have shown in most cases that there is very little difference between the power actually used by the cutter when removing chips either by up-milling or down-milling.

POWER REQUIRED FOR MILLING is a function of many factors, including the cutting speed, the feed, the material being cut, the rake angle, the sharpness of the cutter, the depth of cut, the smoothness of the face of the teeth, the type of cutting fluid used, etc.

An empirical formula which can be used for a rough determination of the power required in milling is

$$\text{Hp.} = KFWD \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [2]$$

where Hp. = horsepower actually used in cutting; F = feed rate, in. per min.; W = width of cut, in.; D = depth of cut, in.; K = a constant which is different for different materials; values are given in Table 12.

In order to obtain the total actual power required to perform a milling operation in any given type of milling machine, it is necessary to add to the result of calculation by formula [2], the idle power required to drive the machine. Idle power varies in relation to the type of milling machine used. However, it generally is found that the idle power is approximately constant within the range of loads encountered in ordinary milling machine operation. For more exact determination of the power involved in milling, the following formula can be used:

$$\text{Hp.} = CWf^a D^b \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [3]$$

where Hp. = actual horsepower used in cutting; W = Width ~~depth~~ of cut, in.; f = feed per tooth, in.; D = depth of cut, in.; C = a constant.

Constants C and exponents a and b are determined by experiment. They vary with the material being cut, the type of cutter used, the nature of the cut and with up-milling or down-milling. O. W. Boston and C. E. Kraus (*Trans.* A.S.M.E., RP–56–1, 1934) discuss the results of tests with a single point tool and of a great number of commercial tests on milling. They present values of C, a and b for three steels, *viz.* S.A.E. 1020, S.A.E. 1112 and S.A.E. 3250, and also a free-cutting leaded brass of analysis Cu, 0.62; Zn, 0.34; Pb, 0.03. Cuts were made both in a groove and on a land, with cutters whose helix angles ranged from 0 to 40 deg., and whose rake angles ranged from 0 to 15 deg. The range of the values of the exponents and constants was as given in Table 13.

The following summarizes the variation of the exponents a and b and the constant C.

With down-milling, C in most cases is lower than with up-milling. In general, C for a 25-deg. rake angle is about 55% of its value for a 0-deg. rake angle, and varies but little for the greater

Table 12.—Values of Constant K

Material	K	Material	K
Cast iron	0.5	Alloy Steel	2.0 to 2.5
Malleable iron	0.8	Brass	0.35 to 0.5
Mild steel	2.2	Aluminum	0.25 to 0.35
High carbon steel	2.2 to 2.5		

Table 13.—Values of Exponents and Constants in Horsepower Formula

	In Groove			On Land		
	a	b	C	a	b	C
1020 Steel	0.70–0.79	0.87–1.07	5450–20,200	0.65–0.74	0.83–0.94	4130– 9,040
1112 "	0.71–0.82	0.82–0.95	5270–12,780	0.68–0.78	0.82–0.90	3710– 8,350
3250 "	0.68–0.77	0.86–0.98	6780–18,450	0.67–0.84	0.85–0.93	5280–13,360
Brass	0.80–0.91	0.89–1.07	3115– 9,540	0.77–0.89	0.86–0.97	2365– 4,785

angles of rake. The value of C remains practically constant with all helix or side rake angles up to 30 deg., with a sharp increase at 40 deg., due probably to excessive metallic distortion of the chip.

The feed exponent a remains practically constant as the rake angle increases, although a slight decrease is apparent for land cutting. It also remains practically constant as the helix increases, except that for extreme values of helix in groove cutting the value of a is high.

The depth exponent d decreases slightly with high rake angles, and increases slightly for high helix angles when milling in a groove. The exponent remains practically constant when milling is on a land.

TYPICAL MILLING JOBS. SPEEDS. FEEDS.—The following are representative examples of good commercial practice:

Automotive Practice.—1. Rough mill cylinder blocks, top and bottom, manifold, bearing cap slots, and valve-cover pads, using Stellite tools: Cutting speed, 110 ft. per min.; feed, 10.5 in. per min.; depth of cut, $^1/_8$ in.; production, 13.6 pieces per hr.; pieces per grind, 200.

2. Mill clutch housing on cylinder blocks, using cemented carbide tools: Cutting speed, 250 ft. per min.; feed, 12 $^1/_2$ in. per min.; depth of cut, $^1/_{32}$ in.; production, 60 pieces per hr.; pieces per grind, 6720.

3. Finish-mill rear end of cylinder blocks, using cemented carbide tools: Cutting speed 250 ft. per min.; feed, 16 in. per min.; depth of cut, 0.015 in.; production, 44 pieces per hr.; pieces per grind, 3168.

4. Mill mounting pads of master cylinder body, using Stellite cutters: Cutting speed, 140 ft. per min.; feed, 11 $^1/_4$ in. per min.; depth of cut, $^1/_8$ in.; production, 130 pieces per hr.

5. Mill bosses on shock absorber body, using Stellite cutters: Cutting speed, 128 ft. per min.; feed, 25 in. per min.; depth of cut, $^3/_{16}$ in.

Table 14 gives data concerning the milling operations on a 12-cylinder automobile motor block.

General Practice.—1. Bottle mold halves; mill parting faces and tongue, using tungsten carbide and high-speed steel cutters: Material, cast iron; cutting speed, tungsten carbide cutters, 170 ft. per min.; high-speed steel cutters, 53 ft. per min.; feed rate, tungsten carbide cutters, 9 $^7/_8$ in. per min.; high-speed steel cutters, 3 $^5/_8$ in.; depth of cut, $^1/_{16}$ in.

2. Roller-spider; mill three cams using high-speed form cutter: Material, steel forging; cutting speed, 78 ft. per min.; feed variable, average, 5 $^1/_2$ in. per min.; depth of cut, $^1/_{16}$ in.; time per piece, 1.22 min.; production, 42 pieces per hour.

3. Transmission case; mill face, using high-speed steel cutters: Material, cast iron; cutting speed, 60 ft. per min.; feed, 5 in. per min.; production, 8 pieces per hr.

4. Compressor cylinder; Material, S.A.E. 1112 steel; high-speed steel slotting cutter: cutting speed, 64 ft. per min.; feed, 5 $^3/_8$ in. per min.; depth of cut, 0.025 in.; production, 229 pieces per hour.

5. Master cylinder body; mill mounting pads, using Stellite face mill cutter: Material, cast iron; cutting speed, 140 ft. per min.; table feed, 11 $^1/_4$ in. per min.; production, 130 pieces per hour.

6. Block plunger feed trip; mill slot and angle using a gang of high-speed steel cutters: Material, S.A.E. 1112 steel; cutting speed, 65 ft. per min.; feed rate, 2.4 in. per min.; depth of cut, 1 $^1/_2$ in.; production, 12 pieces per hr.

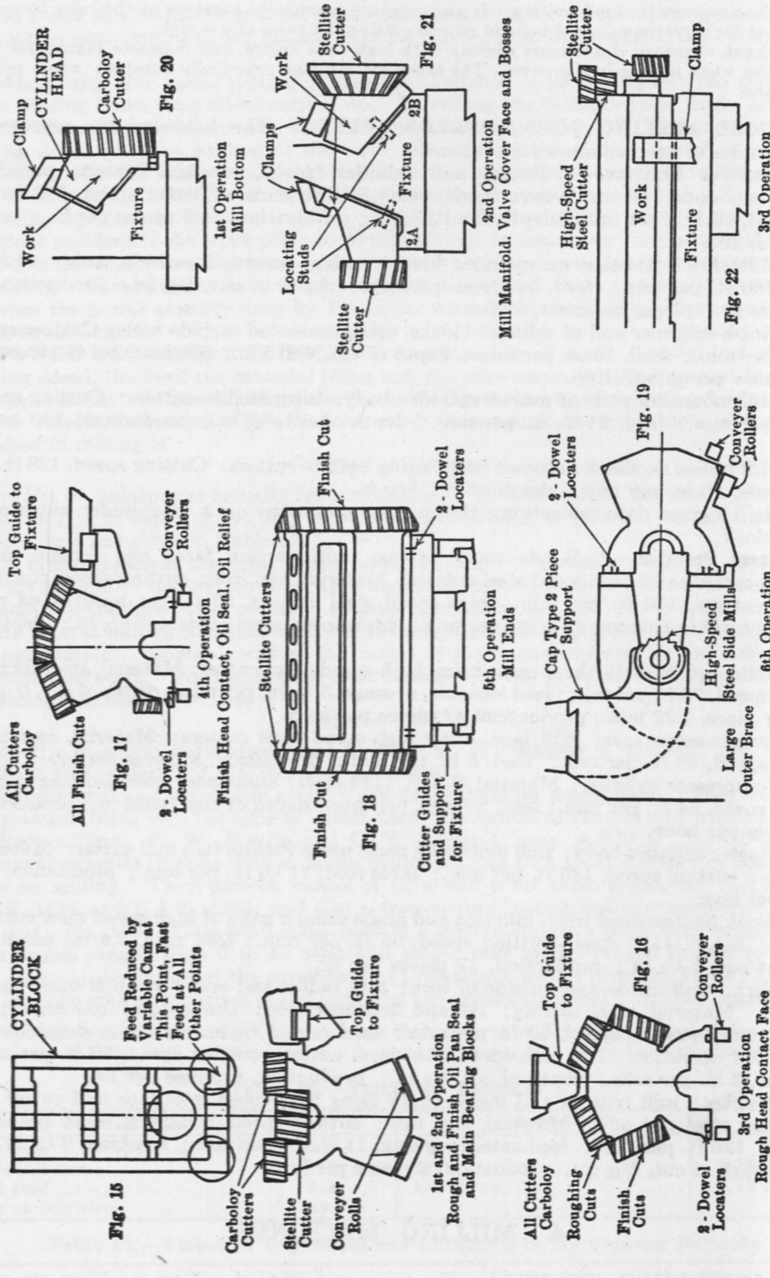
7. Fork; mill inside and outside of fork; mill radius and end, form-mill other radius and end. Material, steel casting; 1st and 2nd operation: Use gang of four high-speed steel cutters; cutting speed, 55 ft. per min.; feed rate, 5 $^3/_8$ in. per min.; depth of cut, $^1/_8$ in. 3rd operation: Use high-speed steel form cutter; cutting speed, 50 ft. per min.; feed rate, 3 in. per min.; depth of cut, $^1/_8$ in.; production, 6 pieces per hr.

8. Bracket; mill bottom and inside edges using high-speed steel face mill cutter and high-speed steel end mill: Material, cast iron; cutting speed, roughing, 80 ft. per min.; finishing, 120 ft. per min.; feed rate, roughing, 11 $^3/_4$ in. per min.; finishing, 9 $^1/_4$ in. per min.; depth of cut, $^3/_{16}$ in.; production, 2 pieces per hr.

4. MILLING MACHINES

CLASSIFICATION AND USES.—The types and sizes of milling machines are numerous and their designs merge into one another. It is, therefore, difficult to classify them. The following classification is based on general appearance or design.

1. Knee and Column Type is so called because the spindle is fixed in the column or main body, and the platen or table is capable of adjustment longitudinally, transversely, and vertically. Machines of this type are of rather universal application and generally


CYLINDER BLOCK
Feed Reduced by Variable Cam at This Point, Fast Feed at All Other Points
Top Guide to Fixture
Carboloy Cutters
Stellite Cutter
Conveyer Rolls
Fig. 15
1st and 2nd Operation Rough and Finish Oil Pan Seal and Main Bearing Blocks
All Cutters Carboloy
Roughing Cuts
Finish Cuts
2 - Dowel Locaters
Top Guide to Fixture
Conveyer Rollers
Fig. 16
3rd Operation Rough Head Contact Face and Finish Water Back
All Cutters Carboloy
All Finish Cuts
2 - Dowel Locaters
Top Guide to Fixture
Conveyer Rollers
Fig. 17
4th Operation Finish Head Contact, Oil Seal, Oil Relief
Finish Cut
Stellite Cutters
Finish Cut
2 - Dowel Locaters
Cutter Guides and Support for Fixture
Fig. 18
5th Operation Mill Ends
Large Outer Brace
Cap Type 2 Piece Support
High-Speed Steel Side Mills
2 - Dowel Locaters
Conveyer Rollers
Fig. 19
6th Operation Straddle Mill Main Bearings
Work
Clamp
CYLINDER HEAD
Carboloy Cutter
Fixture
Fig. 20
1st Operation Mill Bottom
Locating Studs
Clamps
Work
Stellite Cutter
Stellite Cutter
Fixture
2A
2B
Fig. 21
2nd Operation Mill Manifold. Valve Cover Face and Bosses
Work
High-Speed Steel Cutter
Stellite Cutter
Clamp
Fixture
Fig. 22
3rd Operation Mill End and Seal Pad

FIGS. 15 to 22

are selected for that class of production milling which involves relatively small parts, manufactured in limited quantities, with frequent set-ups. They also are used in tool room work and in jobbing shops.

These machines can be equipped with fixtures and multi-spindle attachments to permit their use as production units. Such procedure pays in many shops, where certain jobs are manufactured in sufficient quantities to justify a knee and column type machine for high production, with the idea that it easily can be stripped of its high-production elements and put back on regular run of work.

Knee and column machines are subdivided as follows:

a. Plain Horizontal, with spindle located horizontally.

b. Universal, equipped with a swiveling table, for the cutting of helical grooves.

c. Vertical, with the spindle located vertically.

d. Automatic, which combines the advantages of the bed type and the knee and column type millers.

2. Hand Millers usually are small machines of the knee and column type, in which the feeding movement of the table is controlled by hand. They are used in the manufacture of comparatively small quantities of light parts. Hand millers are subdivided as follows: *a.* Floor type. *b.* Bench type. The latter are used for the machining operations of very light work.

3. Fixed Bed Type machines are intended for use in the manufacture of parts in large quantities, and for this reason they are more rigidly built and simpler than the knee and column type millers. These machines are built on the plan of standard unit construction, which permits the make-up, from standard and complementary units, of a great variety of spindle combinations and feed cycles to meet the specific requirements of manufacture of a given product. See Figs. 15 to 22.

Fixed bed machines often are called semi-automatic, because, with proper fixtures,

Table 14.—Milling Operations Performed on Cylinder Blocks and Heads of a Twelve-cylinder Motor

Operation	Pieces per Hour	Cutters				R.p.m.	Cutting Speed, ft. per min.	Feed, in. per min.	Chip per Tooth, in.	Stock Removed, in.
		No.	Type	Diam., in.	Material					
Cylinder Blocks										
Mill oil-pan face, slot for bearing caps (Fig. 15)	16	2	Inserted-blade face mills	6 1/2	Tungsten Carbide	107	183	19	0.0089	1/8
		1	Inserted-blade end-mill	6 3/4	J-Stellite	64	113	10	0.0098	1/8 to 3/16
Rough-mill cylinder head seats and finish-mill valve cover faces (Fig. 16)	18	2	Inserted-blade face mills	7	Tungsten Carbide	111	204	12 3/4	0.0058	1/8
		1	Inserted-blade face mills	5 1/2	Tungsten Carbide	155	223	12 3/4	0.0052	1/8
Finish-mill cylinder head seats and mill top and water-jacket pad (Fig. 17)	18	2	Inserted-blade cutters	7	Tungsten Carbide	111	204	14 5/16	0.0064	1/32
		2	Inserted-blade cutters	4	Tungsten Carbide	189	199	14 5/16	0.0076	1/8
Mill cylinder block ends (Fig. 18)	13	2	Inserted-blade face mills	18	J-Stellite	31	146	7	0.0057	1/8
Straddle-mill main bearing sides (Fig. 19)	52	6	Half side-mills	6	High-speed steel	49	77	5	0.0085	1/8
Cylinder Heads										
Mill cylinder head bottom (Fig. 20)	24	1	Inserted-blade face mill	7	Tungsten Carbide	110	202	15	0.0069	3/32
Mill manifold, valve cover face and hold-down bosses (Fig. 21)	14	1	Inserted-blade shell end-mill	4 1/2	Stellite	111	131	10 1/2	0.0086	1/8
		1	Inserted-blade formed mill	6	Stellite	86	120	10 1/2	0.0100	1/8
Mill ends and seal pad (Fig. 22)	57	2	Solid shell end-mills	4	Stellite	111	117	8	0.0036	1/8
		1	Shell end-mill	2 1/4	High-speed steel	111	66	8	0.0072	1/8

the work may be clamped and the machine started through a definite automatic cycle, such as rapid advance of work to cutter, cutting feed, rapid return to the starting position, and stop. These machines are subdivided as follows: *a.* Plain (single spindle); *b.* Duplex; *c.* Multiple spindle; rail; bridge; special types.

4. Rotary and Drum Type Millers are provided with fixtures and are used for mass production work in which the cutting is continuous, with no idle time. The parts are loaded on one side of the machine, pass first the roughing, and then the finishing cutters, and return to the loading position, where they are replaced. Drum type machines derive their name from the fact that the parts to be milled are mounted on a drum-like fixture which rotates continuously.

5. Planetary Milling Machines are used to mill plain or formed internal surfaces. The cutter is inserted in the bore to be milled and, while rotating, is fed to depth radially, makes a single sweeping cut about the bore, and is withdrawn first radially, then axially.

6. Thread Milling Machines are designed to cut threads and worms. In these operations milling cutters are used rather than single-point cutting tools.

7. Die-sinking and Profiling Machines are designed to reproduce accurately forms and contours from a master by means of a tracer, contact with which maintains the master form throughout the operation, thus controlling the relative position of work and cutter. These machines are subdivided into:

a. Hand controlled, in which the tracer is guided by hand over the master form.

b. Automatic, where the tracer, once the cycle is started, follows automatically the master form without requiring the assistance of the operator.

MILLING MACHINE ATTACHMENTS.—The range of work that a milling machine can do is greatly increased by the use of attachments. An almost endless variety of attachments has been devised for special requirements. Many of these attachments, however, have become standard equipment units of the milling machine. Among these the most important are the following: 1. Universal dividing head. 2. Index head. 3. Heavy vertical milling attachment. 4. Circular milling attachment. 5. Universal spiral milling attachment. 6. Slotting attachment. 7. Rack milling attachment. 8. Standard index base. 9. Cam milling attachment. 10. Toolmaker's vise.

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